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Summary Report

For

DESIGN AND ANALYSIS OF A CRYOGENIC VARIABLE CONDUCTANCE AXIAL GROOVED HEAT PIPE

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(NASA-CR-137882) DESIGN AND ANALYSIS OF A CRYOGENIC VARIABLE CONDUCTANCE AXIAL GROOVED HEAT PIPE (B K ENGINEERING, INC., TOWSON, MD.) 32 P HC $4.00 CSCL 20D

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1.0 INTRODUCTION

Axial grooved heat pipe technology has been developed extensively for fixed conductance applications in the cryogenic through ambient temperature regime (Refs. 1 through 6). Recently, the axial grooved design has been adapted for use a passive gas-controlled variable conductance heat pipe for ambient temperature operation (Ref. 7). This report summarizes the results of an investigation to adapt axial grocved designs to the gammit of heat pipe thermal control techniques, with particular emphasis on those suited for cryogenic applications. In addition to considering both active and passive gas control, diode designs utilizing liquid or gas blockage or a liquid trap are evaluated. The use of the liquid trap as a secondary heat pipe for forward mode operation during diode shutdown is also studied. This latter function is basically that of a thermal switch. Finally, a system capable of hybrid functions consisting of gas-controlled variable conductance and liquid trap diode shutdown or thermal switching is defined.

This report presents both qualative and quantitative assessments of these various operations. Also, results obtained with a heat pipe breadboard which was used to demonstrate the various operations with ethane at 185°K are presented.

2.0 ANALYSIS

2.1 Axial Grooved Thermal Control Technology

The general field of heat pipe thermal control can be categorized into variable conductance, diode, and switching operational modes. By proper design the axial groove can be adapted to operate in each of these modes. Some special considerations that apply to the axial groove geometry are as follows:

1. The individual grooves must be kept non-communicating for normal operation with conventional designs. When wicked reservoirs are used for variable conductance operation, communication between the condenser and reservoir must be accomplished without causing communication among the grooves.
2. A low "k" feeder tube is required in most gas control VCHP designs to minimize the reservoir volume. An aluminum/stainless steel transition joint is required with present aluminum axial groove extrusions.
3. Existing axial groove designs have a relatively large vapor core. Consequently, optimized gas control VCHP designs should include a plug in the blocked portion of the condenser. This will reduce the amount of gas required and correspondingly the reservoir size.
4. The axial conductance of the ATS aluminum extrusion is 0.20 $\frac{W\text{-}cm}{°C}$ for the 27 fins alone, without including the wall thickness. This is too high for most diode applications unless the transport length between the evaporator and condenser is on the order of 50-cm or greater. A stainless steel axial groove heat pipe would eliminate this problem.

2.2 Variable Conductance Operation

Reservoir size requirements for gas controlled heat pipes are determined from

$$\frac{V_R}{V_{v,c}} = \frac{\psi_o}{\psi_{R_h} - \psi_{R_\ell}} \tag{2-1}$$

where $$\psi_o = \frac{p_v - \pi_o}{T_o} \quad ; \quad \psi_R = \frac{p_v - \pi_R}{T_R} \tag{2-2}$$

with

p_v = System vapor pressure.

π = Partial vapor pressure in blocked condenser or reservoir.

T_o = Sink temperature

T_R = Reservoir temperature.

$V_{v,c}$ = Volume of condenser length blocked at the low power/low sink condition.

V_R = Reservoir volume.

$(\ )_h$ = High power/high sink condition.

$(\ )_\ell$ = Low power/low sink condition.

The ratio of $(V_R/V_{v,c})$ is presented as a function of the change in vapor temperature (ΔT_v), in Figs. 1 through 9 for methane, and also ethane at operating temperatures and sink conditions covering the 100 - 200°K range. These fluids were selected because they have the best transport and wicking height factors over this temperature range. Both active and passive control with a wicked reservoir are considered. The reservoir was assumed equal to the sink temperature except at the low power/low sink condition with active control where it was taken to be equal to the vapor temperature. The vapor temperature difference (ΔT_v) for the passive case is the change that results due to variations in heat load and/or sink temperature. An infinite volume is required to keep the vapor temperature constant. In the active case the reservoir temperature is regulated to give a vapor temperature which will result in the desired control, i. e.

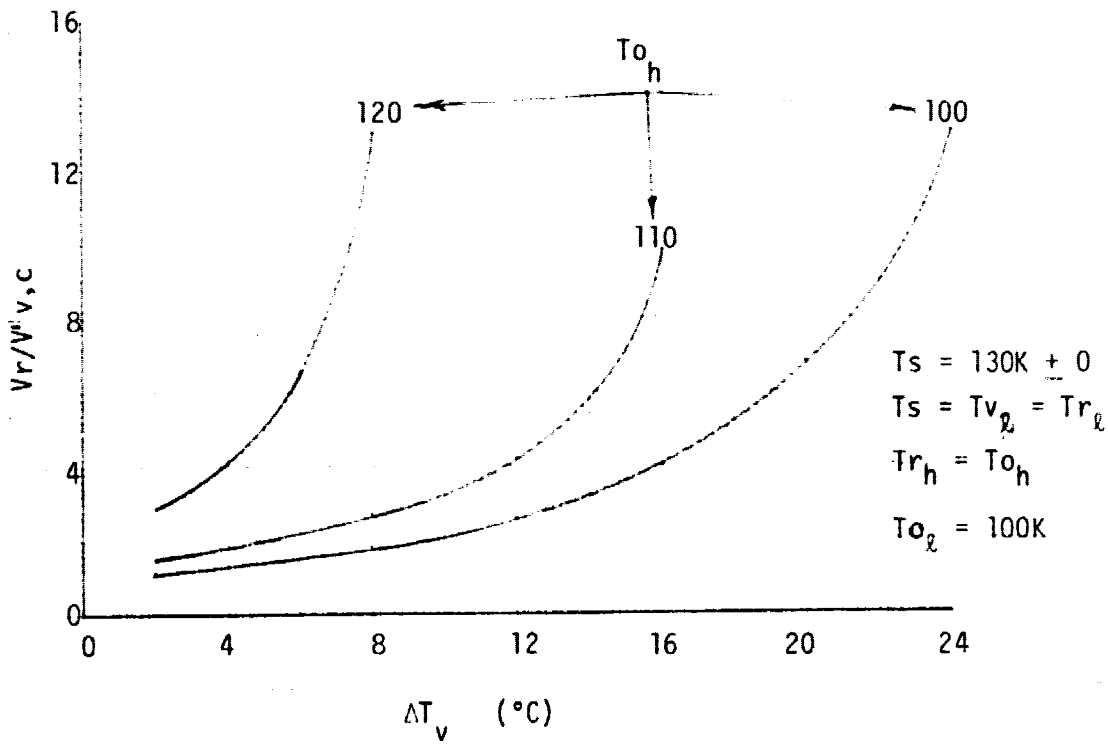


Fig. 1 Reservoir requirements for active control with methane ($\Delta Ts = 0$)

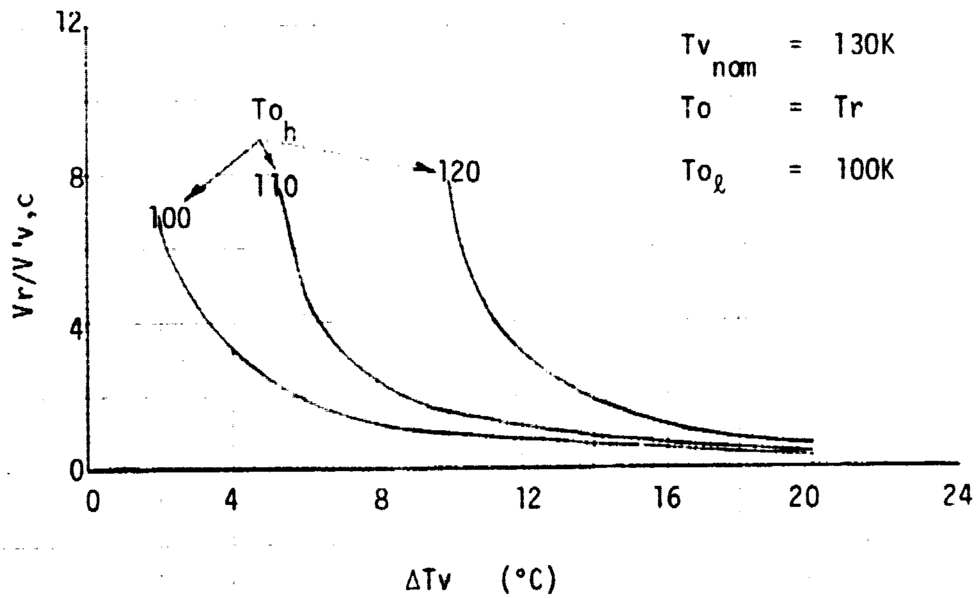


Fig. 2 Reservoir requirements for passive control with methane.

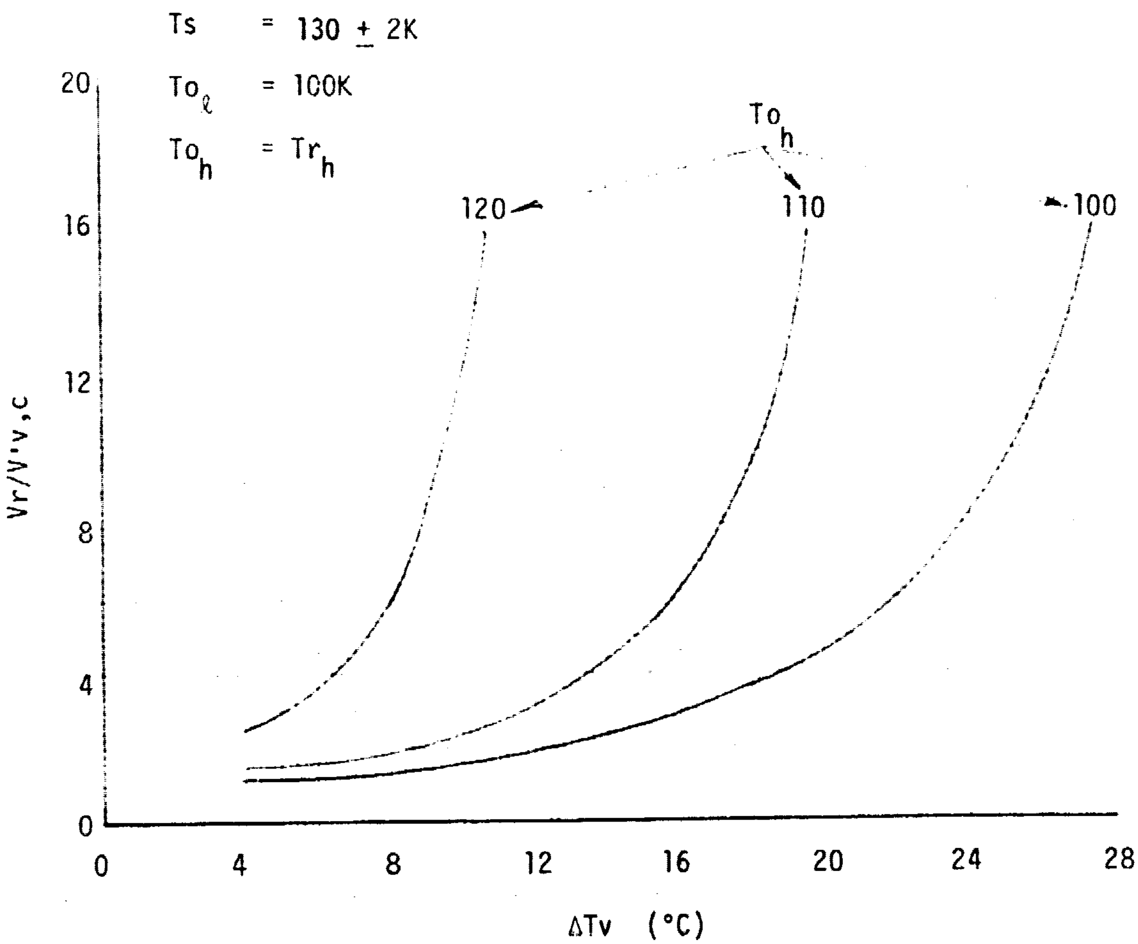


Fig. 3 Reservoir requirements for active control with methane (ΔTs = 4)

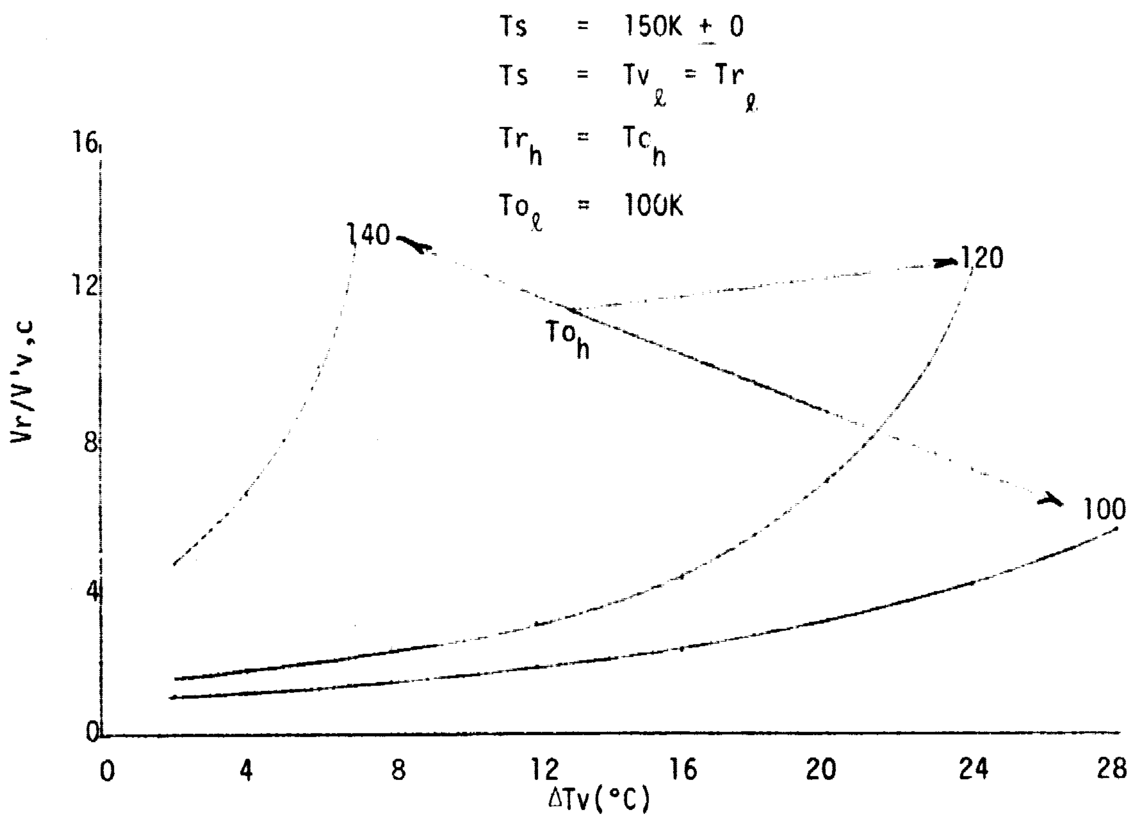


Fig. 4 Reservoir requirements for active control with methane ($\Delta Ts = 0$)

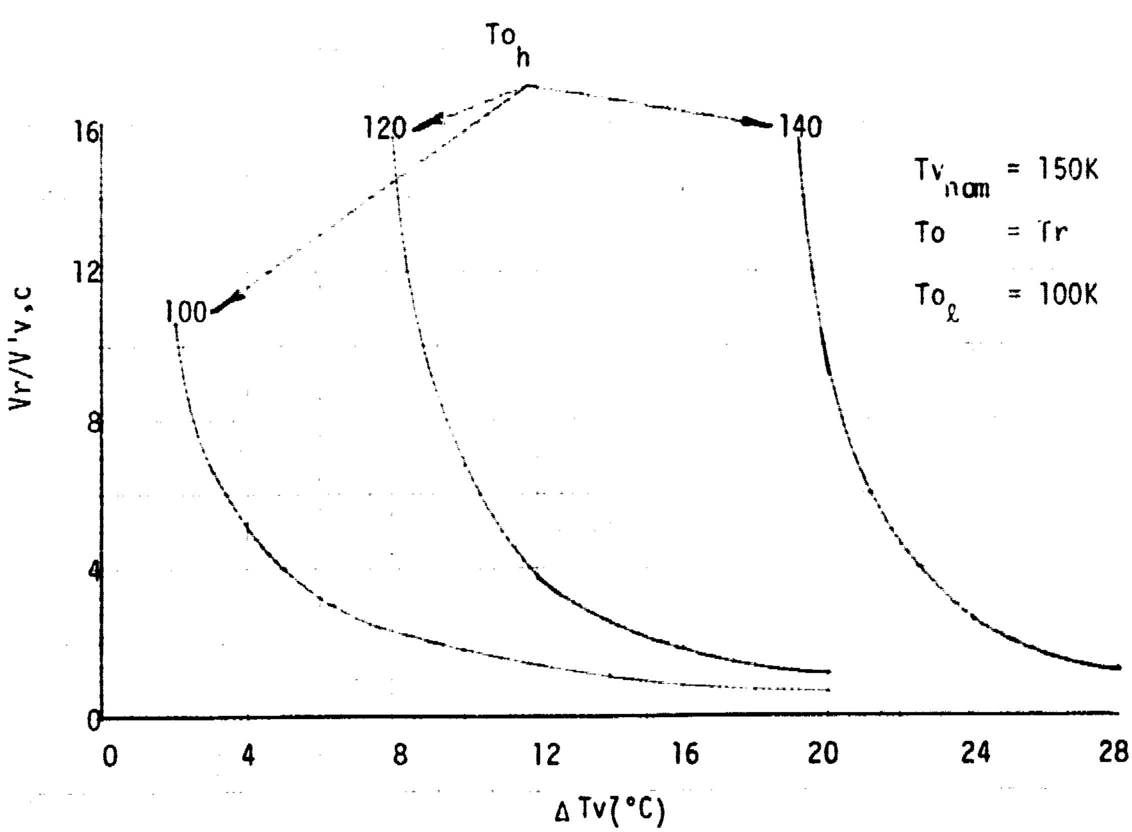


Fig. 5. Reservoir requirements for passive control with methane.

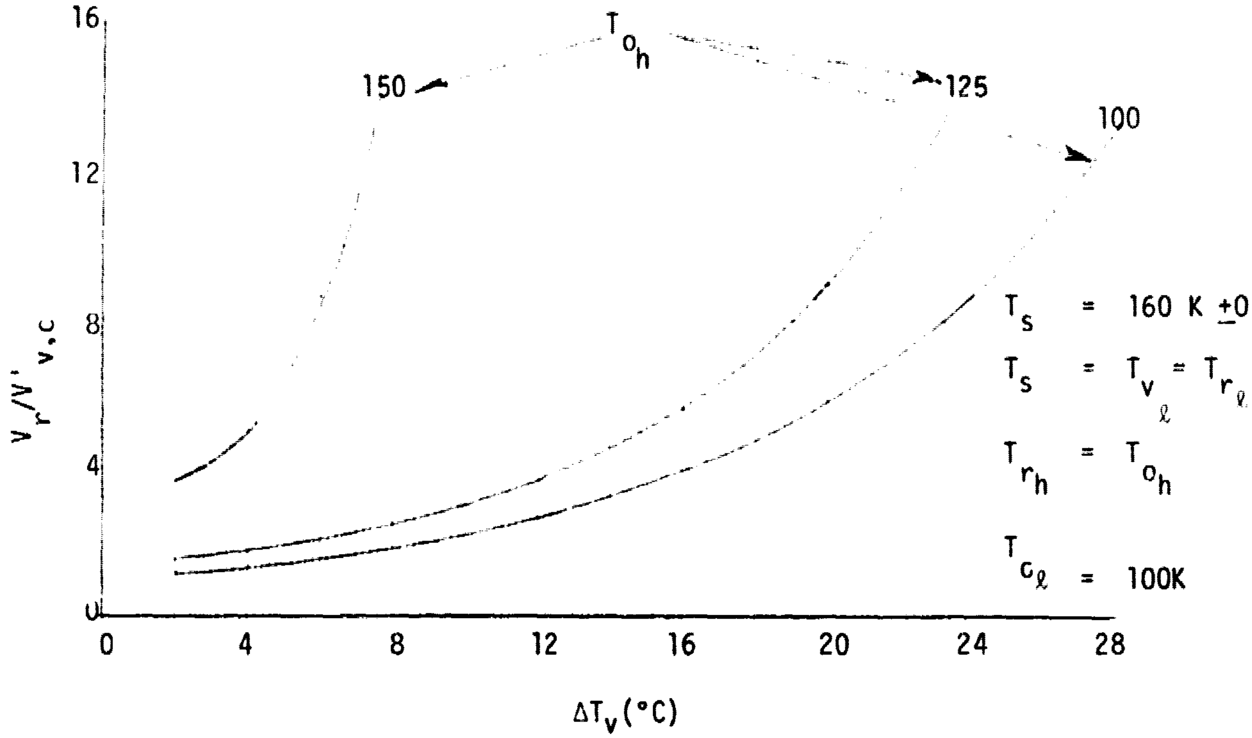


Fig. 6 Reservoir requirements for active control with ethane (ΔT_s=0)

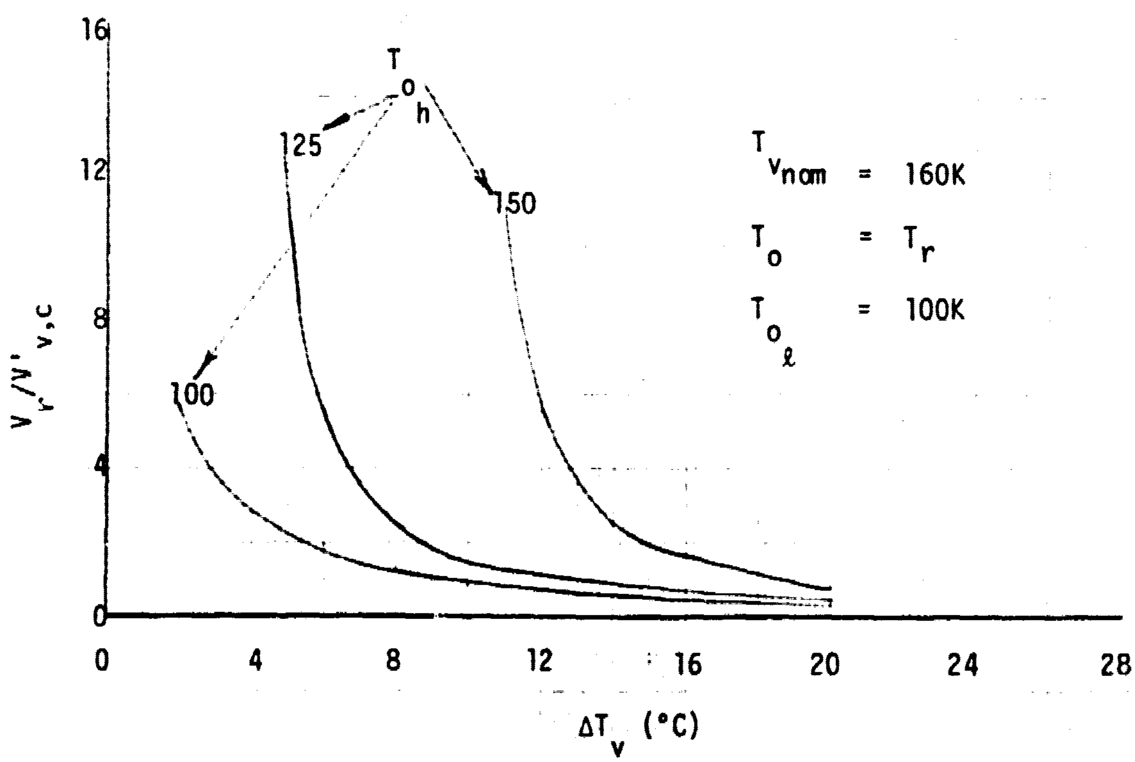


Fig. 7 Reservoir requirements for passive control with ethane.

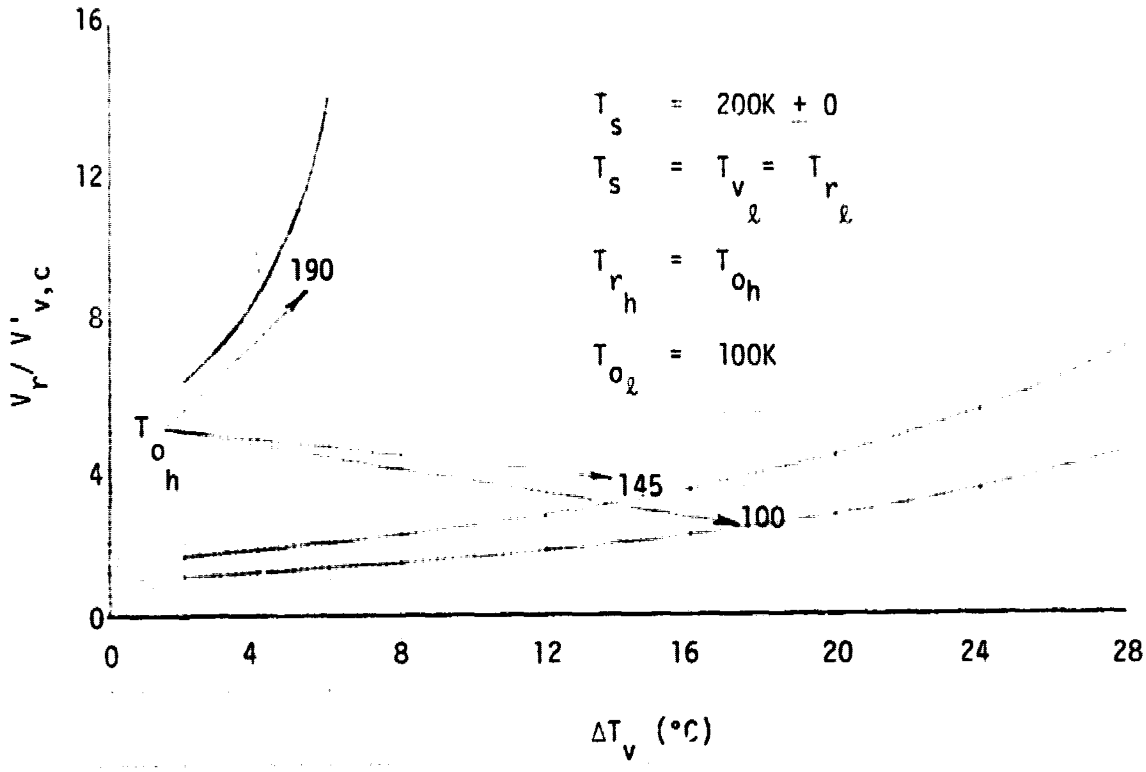


Fig. 8 Reservoir requirements for active control with ethane ($\Delta T_s = 0$)

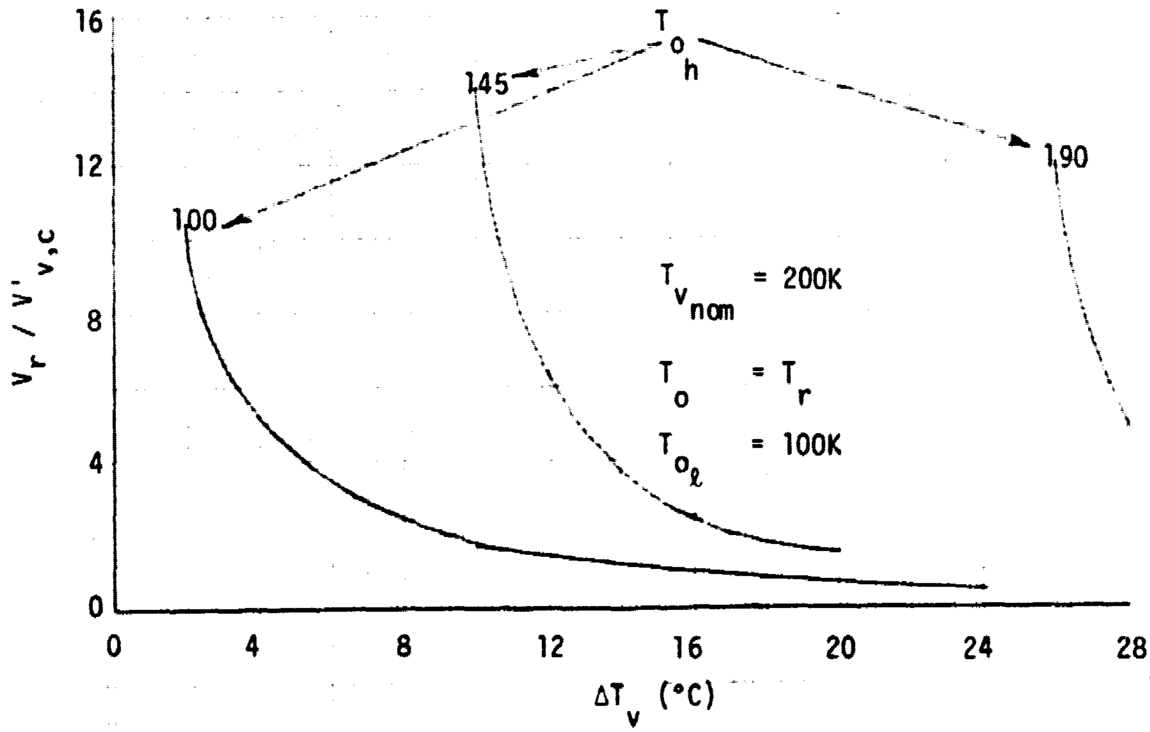


Fig. 9 Reservoir requirements for passive control with ethane

$$\Delta T_v = \Delta T_s - R_s \Delta Q$$

where Q = Heat load

R_s = Thermal resistance between the source and heat pipe vapor.

T_s = Source temperature.

Consequently the larger the swing in vapor temperature required, the larger the reservoir volume.

The results of the analysis indicate that with a typical volume ratio of 10, the vapor temperature variations in the passive system will be less than 4°C provided that the maximum reservoir temperature is at least 20°C below the vapor temperature. In many cryogenic applications the operating temperature will run close to the effective sink temperature and therefore the desired control may be difficult to obtain with a conventional passive system. Passive feedback or vapor modulation may be adequate, however, these are not state-of-the-art systems, and the bellows configurations required may have difficulty containing the pressure associated with cryogenic fluids.

An active system with the same volume ratio will provide absolute control of the source under conditions requiring up to a 6°C vapor temperature swing. This should be more than adequate for most cryogenic applications.

As regards the ATS axial groove geometry, the vapor area is 0.6-cm². Hence 6-cc of reservoir volume are required for each centimeter of blocked length to give the 10 to 1 volume ratio. This volume can be reduced by up to 50% by using a plug in the vapor space with only modest reductions in transport capability.

2.3 Diode Operation

There are several methods for affecting diode operation. Those generally considered are: liquid blockage, liquid trap, and gas blockage. The important parameters to be considered when evaluating diodes are shutdown energy, reverse mode conductance, and reservoir size.

2.3.1 Gas Blockage

Reservoir sizes required for gas blockage are generally an order of magnitude greater than those required by either the liquid blockage or liquid trap techniques. However, when an application requires both variable conductance and diode operation, gas blockage should be considered. In order to meet the shutdown requirements there must be sufficient gas charge to block the evaporator section and a "low-k" section between the condenser and evaporator. The minimum length of the "low-k" section is dictated by the specified shutdown conductance. In many cryogenic applications the length of the condenser will be much longer than the evaporator and "low-κ" sections, in which case the reservoir size required for variable conductance operation would be of the same order or greater than that required for diode shutdown. One potential problem is the amount of energy that will be required to sweep the gas out of the reservoir and shut off the pipe. This is one of the parameters that was evaluated in the test program discussed in the next section.

2.3.2 Liquid Blockage.

Liquid blockage requires blocking the vapor space which in a conventional axial grooved pipe creates communication across the grooves. Although this is acceptable and even desireable in diode shutdown, the potential draining of the grooves that could result in 1-g tests would be misleading, and this technique will not be considered.

2.3.3 Liquid Trap

A liquid trap which does not communicate with the heat pipe wick depletes the liquid from the wick during diode reversal. This method is most promising with an axial groove geometry because this wick type requires a relatively low fluid inventory. It is particularly useful when the condenser length is smaller than the evaporator and "low-k" sections. As discussed in a later section, test results indicate shutdown energies which are approximately equal to the heat of vaporization associated with the grooves' liquid inventory.

2.4 Thermal Switch

One obvious advantage of a liquid trap design is that the trap can be used as a secondary heat pipe to permit forward mode operation while the main pipe is shutdown. One of the potential applications for a cryogenic heat pipe diode is to interface a detector with a passive radiator. If the radiator gets hot, (e.g. due to a cyclic solar input), diode reversal occurs and the pipe is shutdown. The liquid trap could be used to transfer the detector load to an alternate sink (e.g. phase change material) at this time.

Another case would be to use multiple radiators coupled via a single heat pipe switch. In this situation the fluid inventory is depleted from the shutdown portion of the system and transferred to the active radiator and pipe via a non-communicating, interconnecting vapor chamber. Here, there is a combination diode and switching operation. Since an axial groove heat pipe requires a relatively low fluid inventory, shutdown and switching can be accomplished quite rapidly.

2.5 Hybrid Operation

A hybrid system consisting of a VCHP and a liquid trap or thermal switch can be utilized in applications requiring regulated temperature control

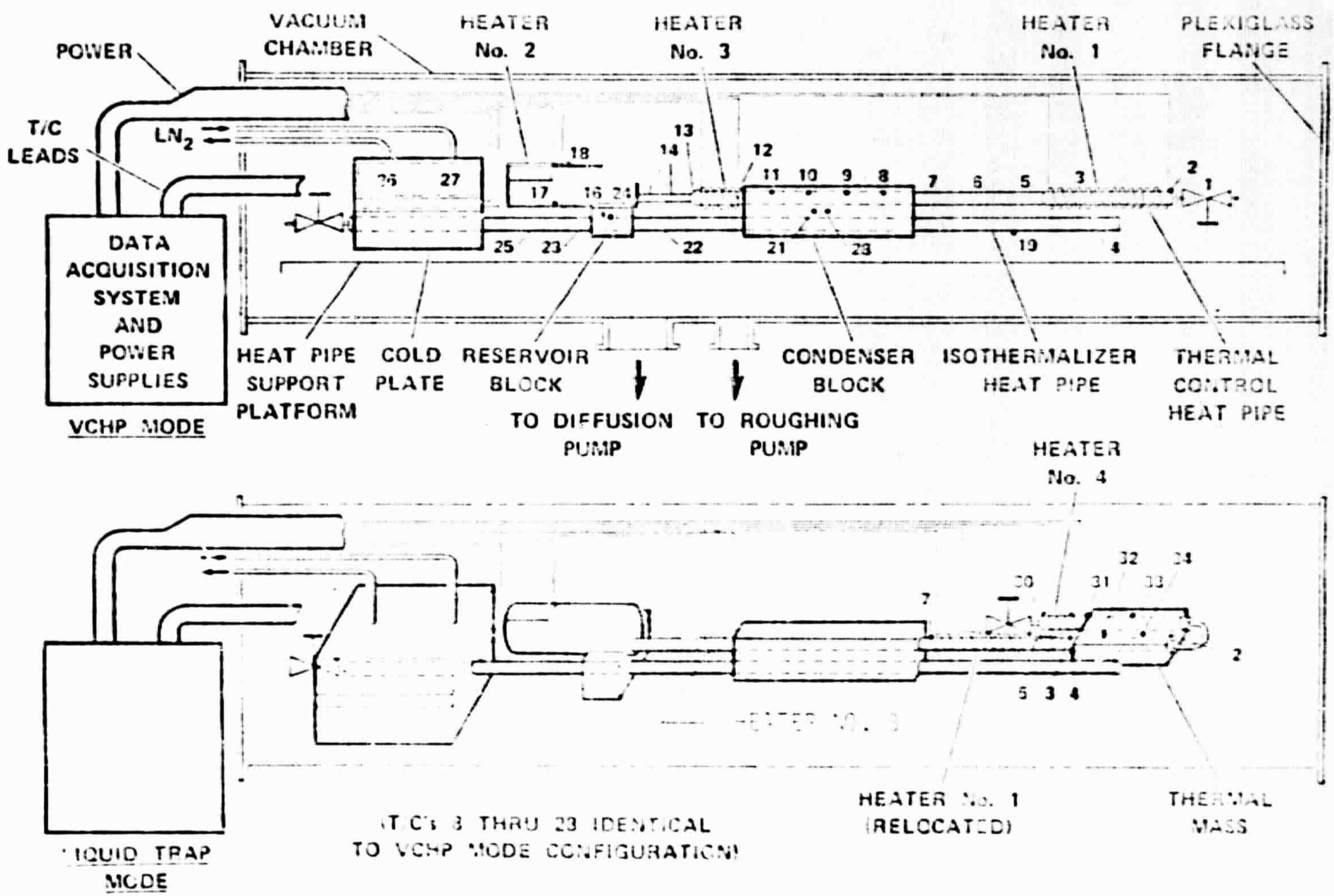


FIG. 10 THERMAL CONTROL HEAT PIPE CONFIGURATIONS AND SET-UP FOR CRYOGENIC TESTS.

TABLE 1. CRYOGENIC THERMAL CONTROL HEAT PIPE DESIGN SUMMARY*

VCHP Configuration	
Heat Pipe	6063 aluminum - ATS axial groove extrusion - 27 grooves, vapor diameter - 0.884
Lengths	
Evaporator	15.2
Transport	15.2
Condenser	20.3
Inactive section (HTR #3)	5.1
Feeder tube	7.6
Reservoir	304 stainless steel (ss) cylinder with 200 mesh - 304 ss screen spot-welded to interior. 15.2 x 5.08 O.D. x 0.124 wall.
Heat rejection surface	4.45 x 5.08 - 304 ss plate.
Liquid Trap Configuration	
Forward Mode	Heat pipe with gas reservoir as per VCHP configuration. Liquid trap is attached to normal evaporator end. Active lengths are changed as per Fig. 1.
Reverse Mode	
Lengths	
Evaporator (HTR #3)	5.1
Transport	2.92
Heat Source (HTR #1)	15.2
Liquid Trap	6061 aluminum cylinder 15.2 x 2.54 O.D. x 0.147 wall-threaded with 72.4 grooves/cm. Contains a centrally located slab wick (0.86 thick) formed from 100-mesh - 304 stainless steel screen

* All dimensions in centimeters.

and also protection from a hot environment. Reservoirs will generally be required at each end of the heat pipe system to accommodate these operations. The test system discussed in the next section demonstrated that these operations could be achieved with a single heat pipe system. The results show no evidence of synergistic effects during shutdown or switching due to the presence of the non-condensible gas.

3.0 TEST PROGRAM

The results presented in this section have for the most part been published in Ref. 8, and are presented here for completeness.

3.1 Heat Pipe Description

A single heat pipe was fabricated which can be configured for operation as either a variable conductance heat pipe (VCHP) or a "liquid trap" diode. Hybrid operation can be demonstrated with the latter system. Both configurations are shown in Fig. 10. Their detailed designs are summarized in Table 1.

3.1.1 VCHP Configuration

The system's baseline design is that of a conventional gas controlled heat pipe. The heat pipe was fabricated from 6063 aluminum-ATS axial groove extruded tubing (Ref. 4). A stainless steel cylindrical reservoir, which provides a 10:1 storage ratio, is interfaced with the pipe via an aluminum/stainless steel transition piece (feeder tube). The stainless feeder tube is required to minimize conduction between the heat pipe and reservoir. This permits optimum gas storage at maximum conditions and minimum reservoir heater power at the low power/low sink condition. Liquid communication between the heat pipe and reservoir is accomplished by several layers of 200 mesh stainless steel screen which extend from the grooves through the feeder tube and are spot-welded over the reservoir's

interior to provide circumferential liquid distribution. Heater wire is wrapped around the last 4.45-cm of the reservoir. This heater (HTR #2) is manually controlled during operation in the feedback mode. The 5.08 x 4.45-cm stainless flat plate, which serves as the reservoir's heat dissipation surface, is soldered to the bottom of the reservoir near its upstream end. Ethane is used as the working fluid and the non-condensible gas is helium. Because of limited liquid nitrogen cooling capacity as well as large temperature drops in the test set-up, the operation above 175°K was required in order to accommodate the maximum heat load (~ 50-W). In addition to having the best transport properties in this temperature range, ethane has also demonstrated predictable performance with this groove geometry.

3.1.2 Liquid Trap Diode Configuration

A liquid trap diode operates on the principle that during reversal, fluid evaporated from the normal condenser will condense and accumulate in a non-communicating reservoir therein drying out the heat pipe. The baseline VCHP design is converted to the liquid trap configuration by removing the valve at the pipe's fill-tube and using Swagelok fittings to connect the fill-tube and trap. The I.D. of the interconnecting tube is 0.39-cm which is sufficiently large to prevent any capillary interaction between the grooves and liquid in the trap. A 0.86-cm wide slab which was formed by continuous wraps of 100-mesh stainless steel screen is used to retain the condensed liquid. Circumferential liquid collection is accomplished by screw thread grooves (72.4/cm) machined into the aluminum reservoir's I.D. The liquid trap is therefore a separate heat pipe which can be used during the diode's shutdown to transfer any applied heat loads. This is basically the function of a thermal switch.

A 0.463 kg aluminum block is coupled to the heat pipe and reservoir. This mass is used during the reverse mode to absorb the shutdown energy, reverse heat flow, and the heat loads applied to the pipe's evaporator (HTR #1) and to the liquid trap (HTR #4). Ethane was again used as the working fluid, but without a non-condensible. Hybrid operation was accomplished by including a helium charge consistent with the VCHP mode.

3.2 Test Set-Up

The system used to conduct the VCHP and liquid trap tests is indicated in Fig. 10. The set-up is virtually identical for both modes; only the test parameters and procedures change. All testing was performed in an ambient temperature vacuum chamber. A cold plate which was cooled with liquid nitrogen is located within the chamber. Heaters inserted into the cold plate are used to provide control at different operating temperatures.

As shown in Fig. 10, an isothermalizer heat pipe interfaces between the cold plate and the thermal control heat pipe (TCHP). The isothermalizer which is also an axial grooved pipe, is used to provide identical sink temperatures at the TCHP's gas reservoir and condenser. Aluminum blocks clamped between the two pipes at these sections provide the thermal coupling. A thin plastic shim is inserted between the reservoir plate and reservoir block to simulate a radiative conductance and avoid excessive reservoir power dissipation during operation in the VCHP mode. Once assembled, each configuration was instrumented with copper-constantan thermocouples and covered with a multi-layer insulation blanket.

3.3 Test Results for Gas-Controlled Operation

A series of tests was run to establish the performance of the VCHP configuration in feedback and passive gas-controlled modes. Passive diode shutdown via gas blockage was also evaluated.

3.3.1 VCHP Behavior

The transient response of the heat pipe's evaporator (TC2) to step changes from a high power/high sink condition to a low power/low sink condition and vice versa is shown in Fig. 11. Operation is in the feedback mode with manual ON/OFF control of the reservoir heater (HTR. #2). The set point was selected as 185°K. The reservoir heater was turned ON when TC2 went above 185.5°K and OFF when it dropped below 184.5°K. Reservoir power was 6.4 W, which was just sufficient to maintain control at the minimum condition with the reservoir at 173°K.

The evaporator heat load was stepped between 8 and 50 Watts during the tests while the sink temperature varied between 138 and 168°K as shown in Fig. 11. Steady-state control was attained to within $\pm$ 1°C of the set point. During the transient there was a 3°C overshoot while the undershoot was only 1.3°C. The undershoot was smaller because the rate of change in sink temperature in going from maximum to minimum conditions is only 69% as fast as when going to the maximum.

The sharp control attained with this system is due to the relatively large storage ratio (10:1) which permits regulation between the two extremes with a relatively small change in reservoir temperature. As indicated in Fig. 11, the reservoir temperature is almost constant. Quasi-steady-state operation at the minimum condition is attained with the reservoir at 173°K. The reservoir cools to 169°K to allow the pipe to open at the maximum condition. Since the heat pipe vapor and ultimately the source temperature (in this case TC2) can recover no faster than the reservoir responds, the smaller the temperature swing required for the reservoir the better the transient response.

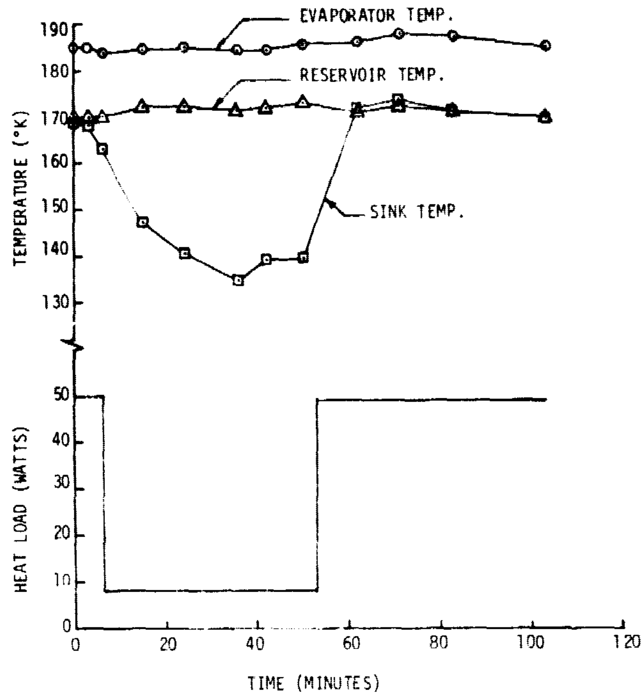


FIG. 11. TRANSIENT PERFORMANCE OF FEEDBACK CONTROLLED HEAT PIPE.

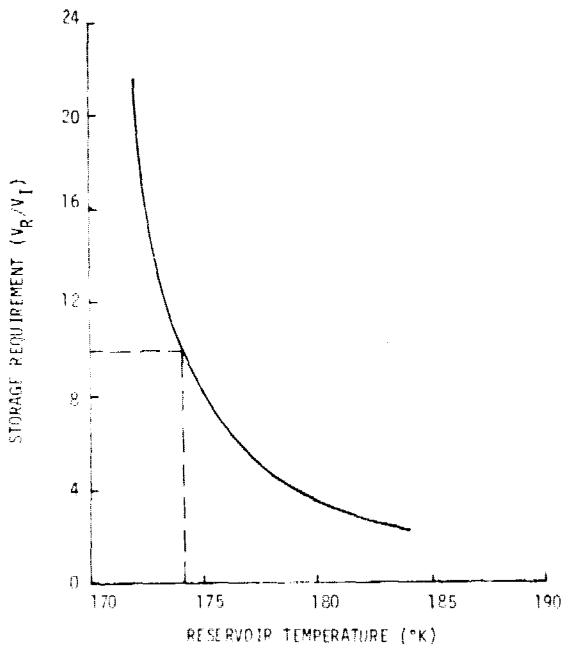


FIG. 12. EFFECT OF RESERVOIR TEMPERATURE (T_{R_L}) ON STORAGE REQUIREMENTS FOR FEEDBACK CONTROL.

The ratio of reservoir to inactive vapor volume required to provide $\pm$ 1°C control at the existing test conditions is shown in Fig. 12 as a function of the reservoir temperature at the minimum condition (T_{R_L}). The predictions are based on "Sharp-Front" theory with the pipe fully open at the high power/high sink condition. An infinite storage reservoir would require a 3°C swing in temperature from 168°K at the maximum condition to 171°K at the minimum. At the other extreme, the smallest storage ratio is 2.25 which corresponds to all of the gas being driven out of the reservoir (i.e. T_{R_L} = 184 K). As indicated in Fig. 12, a reservoir temperature slightly greater than 174°K is predicted for the 10:1 storage ratio provided by the FCHP configuration. Test results show control being attained with the reservoir at 173°K. This small difference is probably due to thermocouple calibration errors and/or slight inaccuracy in the calculations.

Steady-state axial profiles for the feedback mode are compared to those obtained during passive "cold-reservoir" operation in Fig. 13. With passive control the heat source varies from 183 to 163°K as compared to the 185 $\pm$ 1°K control obtained with feedback. A brief study of Fig. 13 will explain the difference in control provided by the two modes. By regulating the reservoir temperature via a feedback controlled heater, the location of the gas-vapor interface and therefore the condenser conductance is adjusted as necessary to give the desired control. The pipe goes essentially from "Full-ON to Full-OFF"as conditions change from maximum to minimum. In a passive system the reservoir follows the sink temperature and the system's control is derived from adjustment by the vapor temperature. Since mass and energy balances require a decrease in vapor temperature corresponding to decreases in heat load and/or sink conditions, source temperature control becomes poorer as the minimum condition is approached.

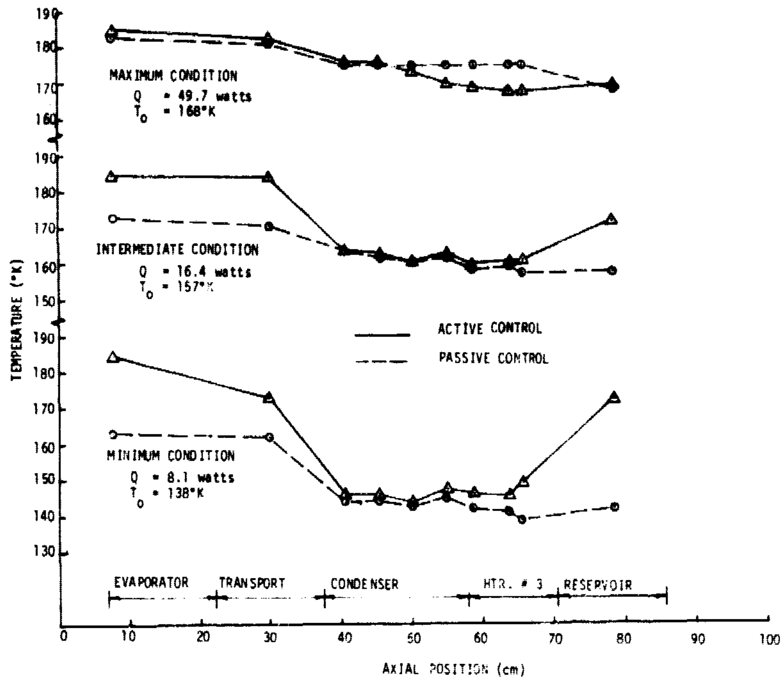
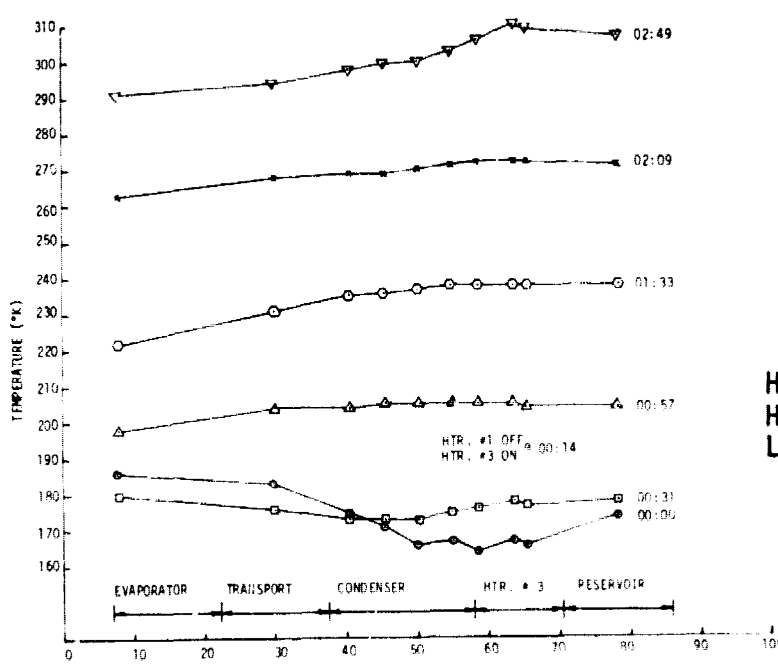


FIG. 13 COMPARISON OF AXIAL PROFILES FOR FEEDBACK AND PASSIVE VCHP MODES.



HTR. #1 OFF
HTR. #3 ON @ 00:14
LN_2 OFF

FIG. 14 TRANSIENT BEHAVIOR OF GAS CONTROLLED DIODE.

As indicated in Fig. 13, the passive system has gas blockage extending through about half of the transport section, and the vapor temperature has dropped to 163°K. The feedback system, on the other hand, because it has the reservoir heated, is shut-off up to the evaporator and nearly perfect steady-state control is achieved.

3.3.2 Gas-Controlled Diode Behavior

Diode shutdown via gas blockage has generally been discounted because the storage volume will be an order of magnitude larger than that required by an equivalent liquid blockage or liquid trap system. However, there are potential applications where both variable conductance and diode operation are required. Since a gas reservoir will be provided for VCHP operation, an increase in its size to accommodate diode shutdown may be acceptable. Consequently, tests were conducted with the FCHP configuration to evaluate diode behavior using gas blockage.

The diode test consisted of starting from a "Full-ON" condition in the feedback mode at approximately 185°K and then going to shutdown with the reverse mode evaporator (TC 13) and gas reservoir temperature (TC 17) increased to approximately 305°K. Axial profiles for the system are shown in Fig. 14 at different times during the reverse mode operation. Once steady-state operation at the maximum condition was attained, the liquid nitrogen and evaporator heater (HTR #1) were turned OFF, and heater #3 was turned ON. An average of 4-Watts was applied throughout the remainder of the test by this heater to establish a reverse mode evaporator. Also, the condenser block temperature (TC 21) was continuously increased so that it was at least 1°C above the reverse mode evaporator. This was done to prevent the condenser block from becoming the heat sink.

Reference to Fig. 14 shows gas blockage in the normal mode condenser with a heat piping action from both ends of the pipe at time 00:31 minutes. As time progresses and the condenser block warms above TC 13, the gas slug moves into the normal mode evaporator region. A close review of the data shows that gas blockage at the opposite end of the pipe begins at 00:39. At 00:57 there is gas blockage into part of the transport section and a 7°C gradient exists across the pipe with TC 13 at 205°K. This gradient increases to a maximum at 01:33 as more gas is swept from the reservoir. Gas blockage covers approximately 40 cm and extends into the normal mode condenser region. The maximum temperature drop is 16°C with TC 13 at 222°K.

Continuous application of heater power causes the reverse mode condenser to rise and correspondingly all other heat pipe temperatures increase. When all of the gas is swept from the reservoir, further increases in the temperature of TC 13 result in compression of the gas-plug and reduced diode shutdown. This is evidenced by the smaller (9°C) gradient that exists across the pipe at 02:09. At this time the gas blockage is across only part of the transport section, and TC 13 has risen to 272°K. This trend continues until the reverse mode evaporator approaches the critical temperature and then "dry-out" occurs (e.g. 02:49 in Fig. 14).

The test results just described are preliminary to the extent that they provide only a qualitative evaluation of gas-blocked diode behavior. Quantitative results require attachment of a large thermal mass or calorimeter to the normal mode evaporator in order to determine shutdown energy and "OFF-conductance". Although the results are preliminary they do indicate what may be the major drawback to gas-blocked diodes. It apparently took 79 minutes from the start of the reverse mode (HTR #3 ON at 00:14) for complete shutdown

to be realized. If this long period is indeed required to sweep all of the gas out of the reservoir, the energy back flow would be prohibitive.

3.3.3 Liquid Trap Test Results

A series of tests were conducted with the liquid trap configuration to establish the performance using this diode technique. Tests were also run to demonstrate the use of the liquid trap as a second heat pipe when the diode heat pipe is shutdown. The test procedure used in these tests is essentially the same as with the gas diode. Once steady-state forward mode operation is attained using heater #1, the liquid nitrogen is turned OFF and heater #3 is turned ON to initiate reverse mode shutdown. Again the condenser block is maintained above TC 13 via separate heater control.

Transient test results for three different tests are shown in Fig. 15 where the temperatures of the reverse mode evaporator (TC 13) and the thermal mass (TC 31) are plotted versus time. The three test conditions can be summarized as follows:

- Test #10 - Baseline diode test, only heater #3 applied during reverse mode operation.
- Test #7 - Same as #10, except that heater #1 is also applied during the reverse mode.
- Test #8 - Thermal switch test, heater #4 which is attached to the liquid trap is applied throughout the reverse mode.

Axial profiles are also presented for each of these tests at different times in Figs. 16, 17 and 18.

The reverse mode behavior is essentially the same for each test.

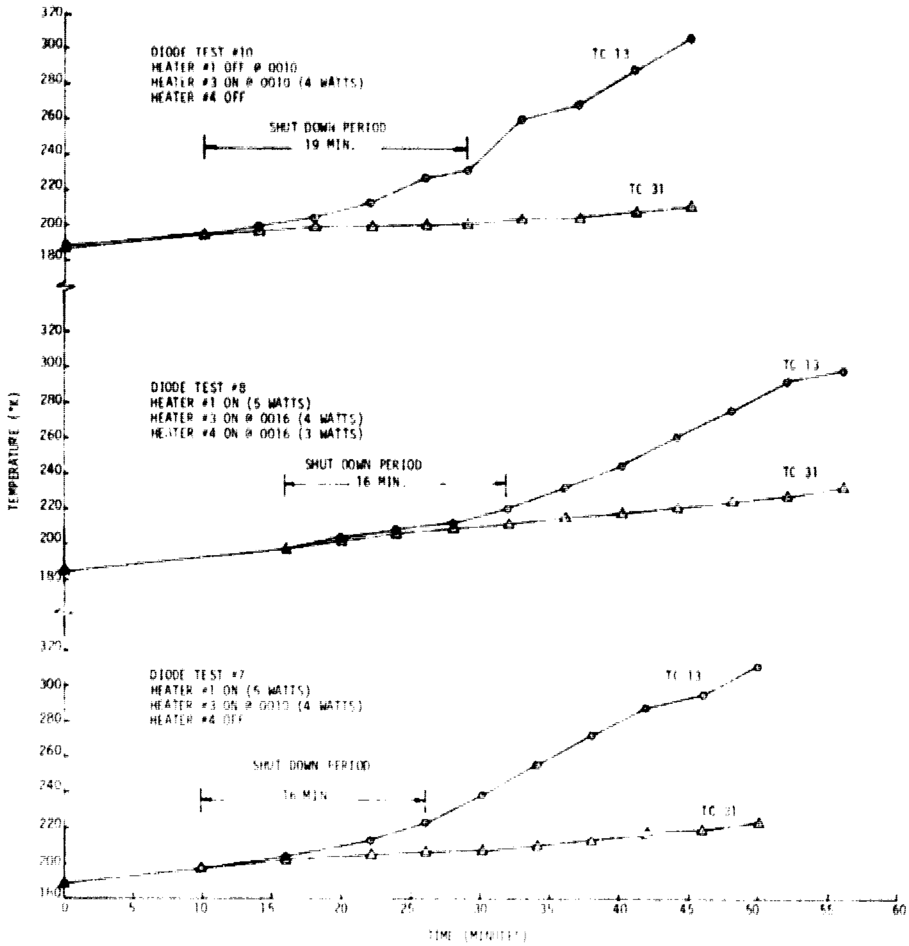


FIG. 15. TRANSIENT SHUTDOWN DURING LIQUID TRAP DIODE TESTS

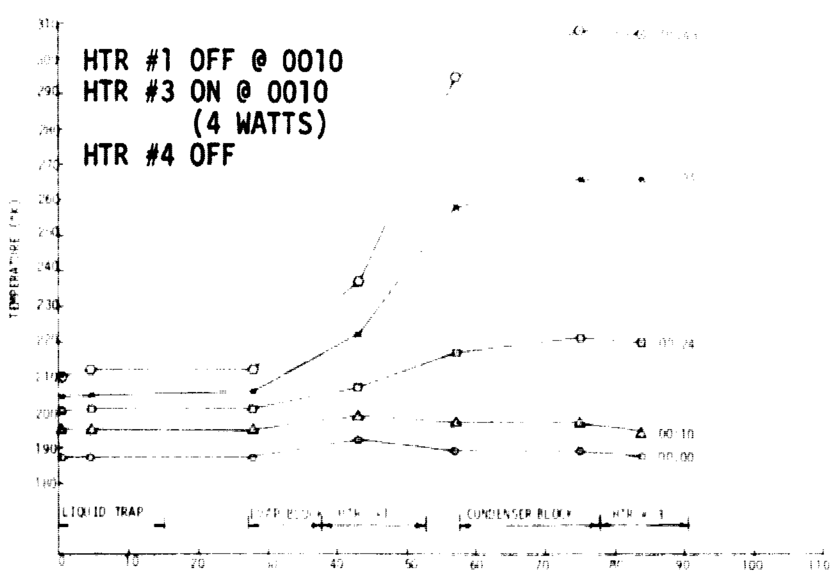


FIG. 16. TRANSIENT BEHAVIOR OF LIQUID TRAP DIODE (DIODE TEST #10)

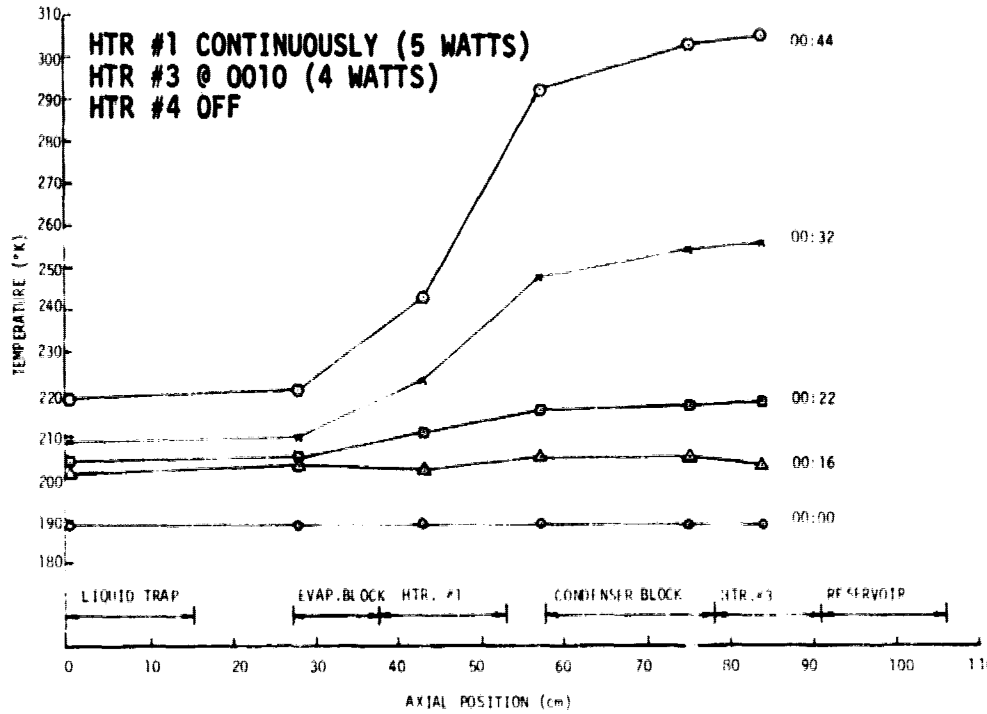


FIG. 17. TRANSIENT BEHAVIOR OF LIQUID TRAP DIODE WITH CONTINUOUS POWER AT THE HEAT SOURCE (DIODE TEST #7)

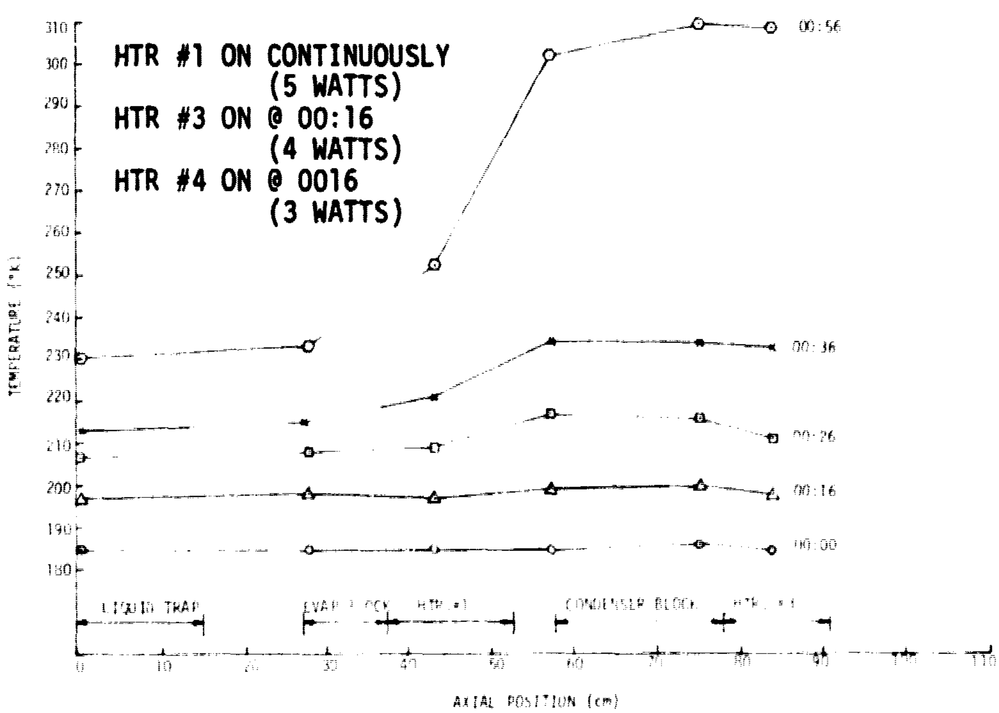


FIG. 18. TRANSIENT BEHAVIOR OF LIQUID TRAP DIODE AND THERMAL SWITCH (DIODE TEST #8)

Within minutes (~ 6) after 4 Watts are applied by heater #3, a gradient begins to develop across the pipe as the reverse mode evaporator drys out. The temperature gradient continues to grow with an increasing rate until all of the fluid is accumulated in the trap. At this time the rate of rise of TC 13 becomes almost constant as indicated in Fig 15 by its linear temperature increase. The rate tends to slow down near the end of the test due to an increase in the backflow conduction associated with the increasing temperature gradient. The temperature response of TC 31 is also indicative of the system behavior. When shutdown is initiated its rate of rise is relatively high due to the reverse flow heat piping action. The rate decreases and reaches a minimum when shutdown is completed and the pipe is dried out. After that time, the rate continuously increases due to the increasing backflow conduction.

Shutdown times and the shutdown energies estimated from the results are listed in Table 2. The shutdown time (t_{SD}) is defined as the time when the rate of increase of TC 31 is a minimum. The shutdown energy is defined as

$$Q_{SD} = (mc_p)_{TM}(T_{SD} - T_o)$$

where $(mc_p)_{TM}$ = Heat capacitance of thermal mass and liquid trap

T_o = Temperature of thermal mass (TC 31) at the start of reversal.

T_{SD} = Temperature of thermal mass at the time of shutdown.

TABLE 2. LIQUID TRAP SHUTDOWN CHARACTERISTICS

Test No.	Shutdown Time (Min)	Shutdown Energy W-HR
10	24	1.05
7	16	1.22
8	16	1.52

The shutdown time and energy have been adjusted for diode test #10 to include the 5 minute interval where TC 13 tends to level off following initial shutdown (Cf. Fig. 15, t = 34 - 39 min.) This second plateau may be associated with a small amount of fluid being removed from the reservoir.

The heat pipe is charged with a total of 18.5 grams of ethane. Its corresponding latent heat energy is 2.5 w-hr at 190°K. Only 5.6 grams are required to fill the axial grooved pipe. The remaining inventory fills the reservoir and provides a slight excess. Since the energies listed in Table 2 are only about half of the total latent heat, the pipe apparently shuts down with the reservoir wick remaining saturated. Also, since the shutdown energy is at most twice the latent heat associated with the axial grooves' inventory, the backflow due to heat piping during reversal is small. This backflow could be further reduced by increasing the conductance between the liquid trap and thermal mass.

As regards the switching operation (Test #8), the slightly higher shutdown energy determined in this test indicates that the operation of the liquid trap as a heat pipe may impede the shutdown slightly. The heat applied at the trap effectively reduces the coupling between the thermal

mass and the trap. In the present configuration, the heat piping action in the trap causes a vapor flow which is opposed to that coming from the axial grooves. In a configuration such as required for a dual radiator, this would not be the case and there would be no impedance from the "Turned ON" pipe.

One final word is appropriate in regard to the reverse mode conductance. The high conductivity of aluminum and the heavy wall extrusion yield an axial conductance of 0.130 W/°C for the 15-cm length between the condenser (TC 7) and TC 5 located in the transport section. Test #10 which does not have any power applied by heater #1 provides a good measure of the reverse mode heat conduction. The rate of increase at the end of the test of TC 31 corresponds to a backflow of 7.78 Watts. There is a 58°C difference between TC's 5 and 7, which corresponds to a backflow of 7.54 Watts. The close agreement indicates that the estimates are accurate. Since only 4 watts are being applied by heater #3, the remaining head load must be due to heat inputs from the condenser block.

3.3.4 Hybrid Operation

Preliminary tests were conducted with the liquid trap configuration charged with helium gas as in the VCHP mode. The tests consisted of running the heat pipe at various power levels and sink conditions in the feedback mode, and then shutdown from the high power/high sink condition to liquid trap diode operation. The preliminary results are essentially identical to those obtained previously in the liquid trap tests. Shutdown energies and times are virtually the same. There are no apparent synergestic effects due to the gas impeding the vapor flow during diode reversal.

4.0 SUMMARY

Cryogenic gas-controlled variable conductance operation has been demonstrated in both passive-cold reservoir and feedback controlled modes

with an ATS axial grooved aluminum extrusion. Temperature control to within $\pm$ 1°C was obtained with feedback versus $\pm$ 10°C with the same system operating in a passive mode. The sharp transient control obtained with feedback was due to a relatively large storage ratio (10:1) which minimized the temperature swing required by the reservoir.

Passive gas diode operation was also demonstrated with this configuration. Although this technique would only be applicable where gas control VCHP operation is also required, the relatively long transient required to sweep the gas out of the reservoir may be prohibitive. Further examination of this method is required.

Test results obtained with the system reconfigured to include a liquid trap showed that this method gives substantially better diode performance. The highest shutdown time was 24 minutes with 4 W applied to the reverse mode evaporator. Therefore at most 1.6 W-hrs went into shutdown. This energy is approximately twice the latent heat associated with the inventory required to fill the axially grooved pipe and indicates that the backflow due to heat piping during shutdown is minimal.

The operation of a thermal switch was also demonstrated using the liquid trap as a second heat pipe. The simultaneous heat piping action by the liquid trap had a negligible effect on the diode's shutdown. Further tests with the liquid trap configuration are desireable.

Finally, hybrid operation consisting of feedback gas control and liquid trap shutdown was achieved with no detectable synergistic effects due to the gas prohibiting vapor condensation in the liquid trap.

In summary each of the various thermal control modes have been demonstrated at cryogenic temperatures. Where quantitative results could be attained they were consistent with theory. Axial grooved wick designs are suitable for the various TCHP operations, however, stainless steel tubing will be required to provide satisfactory "OFF-conductance" for most diode applications. In addition to a "low-k" section which would be provided by a stainless design, an optimized axial grooved VCHP should contain a plug to reduce the vapor space.

5.0 REFERENCES

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